EFFECTS OF PESTICIDE RESIDUES ON SOIL INVERTEBRATES AND PLANTS

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INTRODUCTION

In the last two or three decades, pesticidal chemicals have been increasingly used on agricultural and horticultural crops in Great Britain. Most commercial crops are now treated with either fungicides, fumigants, weed-killers or insecticides; some receive more than one chemical. Along with the benefits pesticides confer by greatly increasing yields, there is growing anxiety about possible long-term side-effects. There are two main dangers. First, that chemicals applied to food crops may not break down rapidly enough and may be eaten by man or animals, but this rarely constitutes a serious hazard; most growers allow sufficient time after spraying for pesticides to be dissipated. However, some pesticides can accumulate in vertebrate tissues from minute amounts taken in with the food and may eventually produce lethal or harmful quantities in animal tissues. Fortunately most pesticides that are sprayed onto plants, or are taken up by plant tissues, break down quite rapidly so that the danger of their being ingested by animals is slight. They do however include some of the more poisonous compounds, and must be used with care.

The second and greater hazard is that pesticides that are applied to, or fall onto soil, may harm plants or soil organisms, and indirectly, higher animals. Even chemicals that break down very rapidly on foliage persist very much longer in the soil, probably because they are less exposed to air or because they become bound to various soil fractions, particularly organic matter. Once in the soil they may affect its complex biological processes by killing animals or micro-organisms. Alternatively, they may be absorbed into plant tissues through the roots, or into small invertebrates, either of which may be eaten by larger animals. They may also kill beneficial animals in the soil, such as predators of pests or of potential pests.

Pesticide residues left on the soil surface break down quite rapidly, but persist longer when buried. When cultivated into the soil, whether by ploughing, rotovation, disking or other operations, they are seldom mixed

to a depth of more than 3–4 in (7·5–10 cm), however thorough the cultivation (Edwards 1964).

Tables 1, 2 and 3 show the commonest types of chemical that may be

TABLE 1
Characteristics of some persistent fumigants and fungicides

Chemical	Persistence in soil (95% disappearance)	Average dosage (lb or gal active ingredient/acre)	Toxicity to mammals (mg/kg)	Plants damaged
Captan	3–6 weeks	1·25–2·5 lb	Low 9000	–
Dichloran	3–4 weeks	4 lb	Low 1500–4000	–
Quintozene	Several months	60 lb	Low 1200	+
Formaldehyde	3 weeks	220 gal	High	+++
Vapam	4–10 weeks	110 gal	820	+++
DD	6 weeks	200–400 lb	High	+++
Chloropicrin	3–6 weeks	560 lb	0·8 mg/litre for 30 min	+++

For footnotes, see Table 3

TABLE 2
Characteristics of the persistent weedkillers

Chemical	Persistence in soil (95% disappearance)	Average dosage (lb active ingredient /acre)	Toxicity to mammals (mg/kg)	Plants damaged
MCPA	2–3 months	0·25–4	700	Annual, some perennial but not graminaceous
2,4–D	4–6 weeks	0·25–4	375	Ditto
2,4,5–T	3–12 months	0·25–4	300–500	Ditto
Amino-triazole	1–4 weeks	4–8	1100	Broad spectrum, especially couch grass
Dalapon	6–8 weeks	4–40	7000–8000	Monocotyledons and perennial weeds
Monuron	1 year plus	10–30	3700	Broad spectrum
Atrazine	Up to 1 year	5–20	3080	Broad spectrum
Propham	Up to 1 year	1–6	1000	Grasses and weed seeds
Simazine	3–12 months	5–20	5000	Broad spectrum

For footnotes, see Table 3

found as soil residues, their possible persistence and potential toxicity to vertebrates and plants. The most transient materials are the fumigants, which usually remain in the soil for six weeks at the most. They are, however, extremely toxic to soil micro-organisms, fungi, invertebrates and growing plants, and at least partially sterilize the soil. Most fungicides except the older copper and mercury compounds have a very low mammalian toxicity, and except possibly quintozene, do not persist long in soil.

TABLE 3
Characteristics of the persistent insecticides

Chemical	Persistence in soil (95% disappearance)	Average dosage (lb or oz.) active ingredient/acre)	Toxicity to mammals (mg/kg)	Plants damaged
Parathion	Up to 6 months	2–6 oz	3·5	−
Diazinon	Up to 6 months	1 lb	125	+
Phorate	4–6 weeks	1½–3 lb	3·7	+
Disulfoton	4–6 weeks	1–2 lb	12·5	−
Carbaryl	Up to 6 months	1½–2 lb	560	−
Aldrin	1–6 years (3*)	1–3 lb	60	+
Dieldrin	5–25 years (8*)	1–3 lb	80–100	−
Lindane	3–10 years (6·5*)	1–2½ lb (5)	125	++
DDT	4–30 years (10*)	1–2½ lb (10)	113	+
Heptachlor	3–5 years (3·5*)	1–3 lb	130	−
Chlordane	3–5 years (4*)	1–2 lb (6)	457–590	−
Telodrin	2–7 years (4*)	¼–1 lb		−

Tables 1–3:

Bracketed figures in column 3 are dosages which may be used for particular pests in exceptional circumstances. Asterisked figures in brackets refer to average persistence. In the last column three plus signs represents very phytotoxic, two, moderately phytotoxic, one, slightly phytotoxic and a minus nonphytotoxic except at very large doses.

Most weedkillers remain in soil for only a short time and few persist for more than a year; 2,4–D and dalapon disappear soonest and monuron and diuron persist longest. Some are selective, killing only a few species of plants; others destroy nearly all plants.

Soil insecticides, particularly the chlorinated hydrocarbons, persist far longer than weedkillers. The organo-phosphorus, carbamate and other insecticides break down comparatively rapidly, and seldom persist in soil for longer than six months, but many are very poisonous to mammals.

Edwards (1964) (Fig 1) calculated from his own results and all the available literature that, of the chlorinated hydrocarbons, DDT persists longest in the soil, as much as 80 per cent remaining one year after

application. After the same time, 75 per cent of dieldrin, 60 per cent of lindane, 55 per cent of chlordane, 45 per cent of heptachlor and 26 per cent of aldrin may be recorded as present by chemical analyses. The residue may not, however, still be in the same form as the insecticide originally applied, so that more or less of the original chemical may remain than the analysis indicates. Aldrin, chlordane and heptachlor break down to other

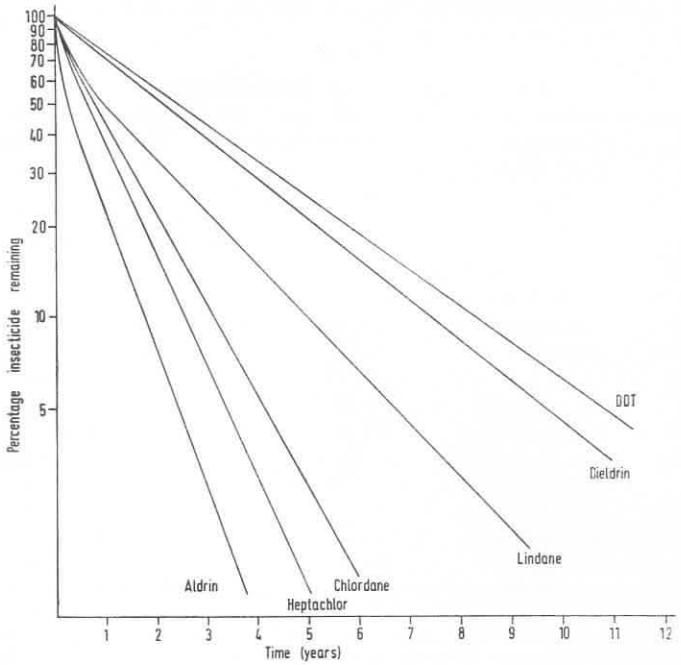

FIG. 1. Breakdown of chlorinated hydrocarbon insecticides in soil (regression based on all available data).

insecticidal compounds not shown by relatively specific analytical methods, whereas lindane breaks down to non-toxic chemicals that are shown by the rather non-specific analytical methods usually used for this pesticide.

In Great Britain, the only evidence available (Wheatley *et al* 1962), indicates that the chemicals most likely to be found in appreciable quantities in soil are DDT and dieldrin; DDT probably originates mainly as 'fallout' from sprays, and dieldrin principally as a breakdown product of aldrin (Table 4). The evidence refers only to potato fields, but as these probably receive more pesticides than many other kinds of agricultural

land, it suggests that very large residues are unlikely to be found elsewhere, except perhaps in orchard soils which probably contain large amounts of DDT which have been washed off foliage by rain.

Chemical residues in the soil can act on plants, fungi, micro-organisms and soil invertebrates, but many other agricultural operations, particularly

TABLE 4
Insecticide residues in potato fields (calculated from data in Wheatley *et al* 1962)

Level of residue lb/acre	No. of fields containing residues (From a total of 21 sampled)				
	Aldrin (15)	Dieldrin (2)	DDT (3)	DDT derivatives	BHC (1) (s.d. 12*)
<0·01	5	2	5	6	13
0·01–0·1	10	8	8	5	7
0·1–0·2	5	7	2	4	0
0·2–0·5	1	1	2	3	0
0·5–2·0	0	3	2	3	1
>2·0	0	0	2	0	0

Figures in brackets are no. of fields treated with insecticide since 1954

cultivation, also affect these organisms. The most usual effect of agricultural practice is to decrease the number of species of soil organisms, and the few species that remain are often able to multiply rapidly until the total numbers are greater than they were originally. The main difference from cultivation is that the effects of chemicals lasts longer; whereas ploughing or rotovation may only change the balance of the soil fauna or flora for a matter of weeks or at most months, persistent chemicals can alter them for months or years.

I. EFFECTS OF PESTICIDES ON SOIL MICRO-ORGANISMS

Fumigants and fungicides are used in soil to kill micro-organisms parasitic on crops, but their effects cannot usually be confined to the harmful forms and many saprophytic and autotrophic organisms are also killed. When a large proportion of the total soil organisms have been killed, some types recolonize faster than others and may become much more numerous than in the original population. Usually, when the chemical has

disappeared, the numbers and types of organisms gradually become similar to those present in untreated soil. Generally, the soil fungi are more susceptible than bacteria and actinomycetes to fumigants and fungicides. The effects of even transient chemicals can sometimes last for a long time, even up to three years.

Fumigants are usually especially lethal to the nitrifying micro-organisms, which oxidize ammonia to nitrites and nitrates, and as these organisms are very slow to return to the soil, ammonia often accumulates in soil that has been fumigated; this may indirectly cause increased plant growth due to extra available nitrogen (Martin & Pratt 1958).

There is a very considerable interaction between weedkillers and soil micro-organisms; many herbicides are broken down in the soil by specific micro-organisms, so these usually increase in numbers in treated soil. There have been many investigations of the direct effects of herbicides on soil micro-organisms, mostly, however, into the effects of 2,4–D. The most general conclusion is that normal rates of application of most herbicides do not injure soil micro-organisms, but very large doses significantly affect the soil population (Newman & Downing 1958). Dalapon tends to stimulate microbial activity; with the other herbicides the slight effects on micro-organisms recorded have been mainly on the nitrifying bacteria (Fletcher 1961).

The effects of insecticides on microbial activity have also been extensively studied, and it appears that although some microbial activity in soil may be disturbed by very large doses of insecticide, amounts large enough to do this are unlikely to occur even as accumulations from frequent field applications. Of the chlorinated hydrocarbons, BHC is most harmful to microbial activity; aldrin and DDT (Eno 1958) and organo–phosphorus insecticides such as parathion (Bollen 1961) have often stimulated bacterial activity in soil.

II. EFFECTS OF PESTICIDES ON PLANTS

Chemical residues in the soil can seriously depress growth or germination of plants, cause chlorosis or wilting, or produce distortion or stunting; sometimes plants take up pesticides which may cause off-flavours or taints in the edible parts of the plant. Some may even stimulate plant growth, in addition to the increased growth from pest and disease control.

It is very difficult to demonstrate phytotoxic effects experimentally except by applying very large doses of chemical to soil. The natural variability in both plants and soil often masks the effects of the chemicals

on the plants, necessitating large and extensively replicated trials to detect significant results in field experiments. Furthermore, different varieties of the same species of plant may respond very differently to a particular chemical residue in soil. Consequently the most reliable experimental results have come from pot experiments, and it may not be reasonable to expect exactly parallel effects in the field. Pesticide residues differ greatly in persistence and effect on pests and plants, in different soil types and climates; this has caused many of the contradictory results in the literature. Toxic doses may differ by as much as ten times in different soil types, probably because the insecticide becomes bound in some soils (Edwards *et al* 1957).

In the present review I have taken the results of my own phytotoxicity experiments wherever available and combined these with other published results to give as general a picture as possible (Table 5). Only common agricultural crops have been considered, because investigations into the effects of pesticide residues on the less important horticultural crops and ornamentals have been too sparse to be conclusive. Results from experiment with chemicals that are unlikely to be found as relatively persistent residues in soil have been ignored.

Fumigants

Fumigants, which have a considerable effect on biological activity, can be very harmful to plants; treatments are therefore usually applied when there is no crop growing and sufficient time is allowed for the fumigant to disperse rapidly, and most crops can be grown safely six weeks after treatment, except in cold weather when the chemicals may persist for several months. The most phytotoxic fumigant is metham sodium and there are numerous instances of damage to crops planted too soon after treatment with this chemical. When plants are grown in soil that has been treated with DD, before all the chemical has disappeared, the plants are likely to become tainted. Formaldehyde, a very commonly used soil sterilant, has sometimes left residues which have damaged plants, and other fumigants leave residues of salts such as chlorides (from DD or chloropicrin), or bromides (from ethylene dibromide) which have damaged a few crops, but this sort of damage is seldom serious.

Fungicides

Fungicides are generally much less phytotoxic than fumigants, but a few are relatively persistent and some can harm crops. For instance, nabam can damage many crops, quintozene, tomatoes and cucurbits, and fungi-

cides containing copper or mercury radicals may leave residues which are injurious to plants. However, fungicide residues are rarely a long-term hazard to plants growing in treated soil.

Herbicides

Herbicides are specifically developed to kill certain groups of plants and thus, persistent residues are a hazard to crops subsequently grown in treated soil. Some of the herbicides with a wide range such as simazine should therefore be used with great care to avoid damage to crops. Dalapon is only moderately persistent, but it is not safe to sow cereals, beans, peas, crucifers or onions sooner than six weeks after treatment. The persistent weedkillers include propham, chlorpropham, monuron, diuron, atrazine and simazine, all of which can harm many kinds of plants. They persist much longer in soils containing much organic matter, particularly the Fen soils, and in such soils can cause a residue problem. In typical agricultural soils, however, the residues seldom persist longer than one year so there is no long-term problem.

Insecticides

Insecticides are not usually very phytotoxic at the dosages normally applied to agricultural land, but accumulations of chlorinated hydrocarbons, after repeated annual treatment with these very persistent chemicals, can reach harmful concentrations.

BHC is the most phytotoxic chlorinated hydrocarbon applied to soil; typically it distorts, scorches and yellows the foliage of many crops grown on land containing moderate to large amounts of chemical. It also produces distinct taints or off-flavours in root crops growing in soil containing sometimes as little as $\frac{1}{2}$ lb of active ingredient per acre (570 g a.i./ha): larger doses may taint the aerial parts of crop plants such as peas, cucumbers and tomatoes. The taint caused by the gamma isomer (lindane) is usually less than that caused by crude BHC. Soils treated with BHC as long as sixteen years ago are still unsuitable for growing root crops because of the taints they cause. Cucumbers, tomatoes and beans are the crops most sensitive to BHC in the soil (Table 5); where there are amounts as large as 100 lb/acre (114 kg/ha) very few plants will grow at all. Cereals are sometimes susceptible to BHC seed dressings and seed treated too long before sowing may germinate poorly, but BHC in small amounts stimulated growth of seedlings of swedes, parnsips, beet, beans

and mangolds although larger doses inhibited germination (Maclagan 1957). Yields of cereals and beet have been decreased with BHC at 15 lb a.i./acre (16·5 kg/ha) (Boswell 1955) and beet and potatoes destroyed completely by doses of 27 lb a.i./acre (31 kg/ha) (Morrison 1948). Tomato growth has been retarded by 8 lb a.i. of BHC/acre (9 kg/ha). The growth of carrots has been stimulated by very low doses of BHC (Boswell 1955) and other workers found a similar effect on turnips.

DDT is only slightly toxic to a few crops, unless used at very large dosages; tomatoes, cucumbers and beans are the most sensitive crops to this chemical (Dennis & Edwards 1964). Peas and other legumes are moderately susceptible, being effected by doses of about 20 lb a.i./acre (23 kg/ha), and some cereals, particularly rye (Boswell 1955) and barley are affected by doses exceeding 20 lb a.i./acre. The growth of beet has also been affected by amounts of DDT greater than 25 lb a.i./acre (28 kg/ha) (Foster 1951). The symptoms of damage are usually general chlorosis of the foliage, some distortion of the leaves and growing point and a depression of growth. The growth of carrots and to a lesser extent of parsnips and turnips has actually been stimulated by DDT in the soil.

Aldrin is rather more phytotoxic than DDT and has caused damage to cucumbers, tomatoes, beans, beet and cereals at quite moderate dosages. It has seriously affected germination of cereals; oats and rye are the most sensitive, germinating poorly in soil with more than 8–16 lb a.i./acre (9–18 kg/ha), winter wheat is affected only at dosages above 16 lb a.i./acre and barley can resist any influence on germination up to 32 lb a.i./acre (36 kg/ha) (Cox & Lilly 1952). Typical symptoms of damage to young cereals are 'angling' of the tender seedlings after emergence through the surface. General symptoms of damage to other crops are marginal leaf scorch and bronzing, slightly twisted growing points and some chlorosis and wilting.

Chlordane and heptachlor are much less commonly used in Great Britain than the other chlorinated hydrocarbons. Chlordane can be rather phytotoxic. Dosages as small as 25 lb a.i./acre (28 kg/ha) have depressed the growth of vegetables (Foster 1951) and germination of seedlings was severely affected by corresponding amounts (Cullinan 1949), but this has not been entirely confirmed by other workers. Certainly, cucumbers are very sensitive to chlordane and beans moderately so (Morrison 1948).

Dieldrin is the least phytotoxic of all the chlorinated insecticides and even at very large dosages it has harmed no crops, except for some slight effect on cucumbers and tomatoes.

TABLE 5
Effects of pesticide residues in soil on some agricultural crops

Chemical	Crop								
	Potatoes	Beet	Carrots	Beans	Peas	Tomatoes	Cucumbers	Crucifers	Cereals
Aldrin	+	+	× +	++	NK	++	+++	+	++
Dieldrin	○	○	○	○	○	+	+	○	○
DDT	○	+	−−	++	+	++	+++	+	+
BHC	× ++	× ++	× ++	++	× ++	× ++	× +++	+	++
Heptachlor	○	+	○	+	NK	+	++	○	○
Chlordane	+	+	−−	++	NK	++	+++	○	+
Parathion	○	+	−−	○	+	−−	++	+	+
Carbaryl	NK	NK	NK	NK	++	NK	NK	NK	++
Diazinon	NK	NK	NK	NK	NK	++	++	NK	NK
Quintozene	○	NK	NK	NK	NK	++	++	NK	NK

× Off-flavours occur.
−− Growth stimulated.
○ No effect.
NK Not known.

+++ < 5 lb/acre. } Phytotoxic
++ 5–20 lb/acre. } symptoms
+ > 20 lb/acre. } caused.

Large residues of the organo-phosphorus insecticides are unusual in soil, but parathion, diazinon, disulfoton and trithion may persist for as long as eight months (Mulla 1961), so they cannot be altogether ignored. Most of them are not very phytotoxic and small doses may even stimulate the growth of some crops; this particularly applies to parathion which has stimulated the growth of tomatoes, carrots and to some extent beans (Boswell 1955). Diazinon is a little more phytotoxic than parathion, particularly to such sensitive crops as cucumbers and tomatoes. Carbaryl, a carbamate insecticide, has damaged peas and cereals but only at quite large dosages.

All these phytotoxic effects should be considered in relation to the likelihood that the residues in agricultural soils probably seldom exceed 2 lb a.i./acre (2·2 kg/ha) at the present time, although in some horticultural and orchard soils they may be greater.

III· EFFECTS OF PESTICIDES ON SOIL INVERTEBRATES

Soil contains immense numbers of small animals, some of which are phytophagous, others saprophagous or coprophilous, and some predatory; there may be as many as 900,000 invertebrates in a single square metre of soil (Murphy 1953). It is still not clear how important animals are in the soil biological processes, and how changes in their numbers may influence formation, structure or fertility of the soil.

Phytophagous animals feed mainly on plant roots, and hence many are pests, or on leaf tissue which falls onto the soil; the saprophagous species feed either on decaying leaf material or on the succession of micro-organisms that grow on plant remains. There is evidence (Edwards & Heath 1963), that leaves of many deciduous trees do not break down until they have been fed upon by soil animals, which allows micro-organisms to enter the tissues and continue decomposition. Soil invertebrates may also pass humified tissue through their guts and hence be important in the later processes of soil formation.

Certainly, burrowing animals, particularly earthworms, enhance the mixing of soil and greatly improve soil aeration and drainage. In the tropics, nest-building social insects, such as ants and termites, which take the place of earthworms in translocating and breaking up large quantities of soil, are very susceptible to insecticide residues.

Populations of soil animals fluctuate greatly during the year, many reaching peak populations in autumn, with numbers becoming few in

the late winter. The cultivation of arable soils often kills a large proportion of the soil invertebrates in them, but populations usually recover after about six months or less; nevertheless, cultivations cause very variable populations of animals. Transitory chemicals probably have a similar effect on soil animals to cultivations, but chemicals that persist for several months, or that almost sterilize the soil, have effects that probably persist for more than one season.

The effects of pesticide residues on the soil fauna depend very much on the form and place in which they occur. Chemicals on the soil surface break down very much faster than those cultivated into soil, which disappear less by volatilization and weathering. Once they are incorporated into soil they persist longest in undisturbed soil; every cultivation brings some chemical to the surface and slightly accelerates its disappearance. Most pesticide residues remain in the top 4 in of soil however thoroughly they have been cultivated into the soil; consequently animals that spend a large part of their life cycle below this depth are usually little affected by the chemical.

It is very difficult to mix small quantities of a chemical evenly through soil; the more thoroughly it is mixed, the more soil animals are likely to be affected. The chemical inevitably ends up as discrete particles scattered through the soil, and this has two effects: first, the smaller the organism, the larger is the portion of its living space likely to be uncontaminated by the chemical and the less the likelihood of its being affected. Secondly, the more active the animal, the greater the probability of it being affected by chemicals as it moves through soil and gradually picks up a lethal dose of pesticide. Because saprophagous species are usually less active than predatory ones, they are usually less affected by chemical residues. For instance, more usually predatory mites are killed than saprophagous ones and the active surface-dwelling (hemiedaphic) springtails more than those in deeper soil (euedaphic.)

Chemicals may affect animals other than by killing them; they may repel them to deeper soil, as does chloropicrin, and there is some suggestion that sublethal doses of pesticide may affect the reproduction rate (van der Drift 1963). At the present time there is little evidence that soil animals have becomes resistant to soil pesticides except in occasional instances such as the cabbage root fly, but it has been suggested that many plants and micro-organisms can become tolerant to chemicals in the soil.

Investigations into the general effects of soil pesticides on soil animals have largely been confined to the more persistent chemicals (Sheals 1956, Edwards & Dennis 1960). Our results to date are summarized in Table 6,

TABLE 6
Effects of chemical residues on soil invertebrates

Chemical	Soil invertebrate									
	Predatory mites	Other mites	Euedaphic Collembola	Hemiedaphic Collembola	Sym-phyla	Diptera	Coleoptera	Lepidoptera	Hemiptera	Earthworms
Aldrin	○	++	++	+++	+	+++	+++	++	+	○
Dieldrin	○	++	++	+++	+	+++	+++	++	+	○
Telodrin	○	++	++	+++	+	+++	+++	++	+	○
DDT	+++	+++	−−	−−−	++	++	++	+++	++	○
BHC	++	+++	−−	−−	++	+++	+++	+++	+++	○
Heptachlor	+	+++	+	+++	+	+++	+++	NK	NK	++
Chlordane	+	+++	+	+++	NK	+++	+++	NK	NK	+++
Carbaryl	○	○	+++	+++	NK	NK	NK	++	NK	+++
Parathion	++	++	++	++	+++	++	++	○	NK	+
Diazinon	++	++	++	++	+++	++	+	NK	+++	○
Menazon	○	○	○	○	○	○	○	○	+++	○
DNOC	○	○	○	+	○	+	○	+	○	+
Simazine	+++	+	++	+++	○	++	++	○	○	++

○ No effect on numbers.
−− Increase in numbers.
−−− Large increase in numbers.
NK Not known.
+ Little reduction in numbers.
++ Moderate reduction in numbers.
+++ Large reduction in numbers.

with other workers' data for carbaryl (Aspok & an der Lahn 1963), menazon (Raw 1963) and DNOC (van der Drift 1963). There has been very little work on soil *fungicides*, but most of these are not very toxic to animals and do not persist long in soil. Exceptions are the copper fungicides which can almost eradicate earthworms from the soil onto which they fall (Raw 1962). Orchards with large residues usually have a poor soil structure and a thick mat of undecomposed leaf tissue.

The effects of *fumigants* have been thoroughly investigated by Buahin & Edwards (1962), who have also considered how sterilized soil is repopulated. Fumigants persist for 3 months at most in soil, but their effects on soil animals can be so drastic that it may be several seasons before the soil population returns to its original size and structure.

Metham sodium, applied as a surface treatment, killed all the animals within the top 6 in (15 cm) of soil; DD, which is usually injected into the soil at a depth of 6 in (15 cm), killed all the animals in the top 12 in (30 cm) of soil. It is surprising that, although the kill is so extensive, it is the soils that have the largest population before treatment that are recolonized first. This is probably because eggs and other resting stages survive fumigation, and because recolonization from the surrounding areas is more rapid. The first animals to return to treated soil are the surface-dwelling (hemiedaphic) Collembola and dipterous larvae, and the surface soil is usually recolonized before the deeper soil. The species that recolonize first increase rapidly so that often there are more of them than in untreated soil, *i.e.* there are fewer species present but these are freed from competition and become more numerous. The effects of the treatments may persist much longer than the chemicals, and even after about eighteen months, treated soils may contain fewer animals, although no chemical remains.

The effects of *weedkillers* on soil animals are being studied by the author in collaboration with G.D. Fryer.* The chemicals so far tested are MCPA representing a phenoxyacetic acid type, tri-allate, a volatile persistent carbamate, simazine, a triazine, and linuron the substituted urea type. Of the herbicides, only simazine affected soil animals, reducing numbers to one-third to one-half of those in untreated soil. The predatory mites and hemiedaphic Collembola, particularly the Isotomidae, were most affected by simazine, but the earthworms, enchytraeid worms, dipterous and coleopterous larvae, and populations of other mites and springtails were all decreased, and significant differences between the numbers of

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these in treated and untreated soil were still obvious three to four months after the chemical had been applied. In other experiments (Nolte 1940, van der Drift 1963), DNOC slightly affected the surface-dwelling soil invertebrates, particularly the Collembola, dipterous and lepidopterous larvae and earthworms.

Because *insecticides* are selected for their toxicity to arthropods, they probably have the greatest influence on soil fauna. Most insecticides applied directly to soil have been selected for their persistence, so that a single treatment with a soil insecticide may protect crops for several seasons. It is only recently that this persistence of the soil insecticides has caused anxiety; several of them appear to persist so long in soil that regular applications may well produce undesirable accumulations of these chemicals. The effects of aldrin and DDT have been most thoroughly studied, principally because these are the chemical residues most commonly found in agricultural soils.

Aldrin has very little effect on the numbers of predatory mites (Fig 2), which is a favourable characteristic because these mites often eat the eggs and young stages of pest arthropods. It does, however, affect saprophagous mites, some of which may be important in decomposing organic matter. Populations of most species of Collembola, which are also saprophagous, are much reduced in numbers, the more active species which live close to the soil surface often being almost eradicated. Symphylids, which live mainly in deeper soil below the residues, are little affected. Both dipterous and coleopterous larvae are almost all killed, especially when the insecticide is thoroughly mixed into the soil. Root aphids and caterpillars are not very susceptible to aldrin, and numbers of nematodes, earthworms and enchytraeid worms are completely unchanged even by large doses. The only probable harmful effect resulting from aldrin in soil seems to be fewer saprophagous mites and springtails.

The effects of dieldrin resemble those of aldrin; this is not surprising, for they are closely related chemically and a proportion of the aldrin residues in soil break down to dieldrin, which is much more persistent, so that ultimately the only residues left from aldrin treatments is dieldrin. Similarly, telodrin, another insecticide related to aldrin, kills almost the same animals as aldrin and dieldrin but does so at much smaller doses. Telodrin is not, however, used in Great Britain at the present time.

The other insecticide commonly remaining in soil is DDT which is less lethal to soil animals than aldrin and dieldrin. It readily kills predatory mites (Fig 2), however, especially at large doses such as occur in some orchard soils; it also kills saprophagous mites. The most striking feature

about DDT-treated soil is the large increase in the numbers of Collembola, which occurs at all doses of DDT. tested; the increase differs at various times in the year, but in some seasons springtails in DDT-treated soil may be ten times more numerous than in untreated soil. Very large populations of springtails are common in agricultural and glasshouse soils regularly

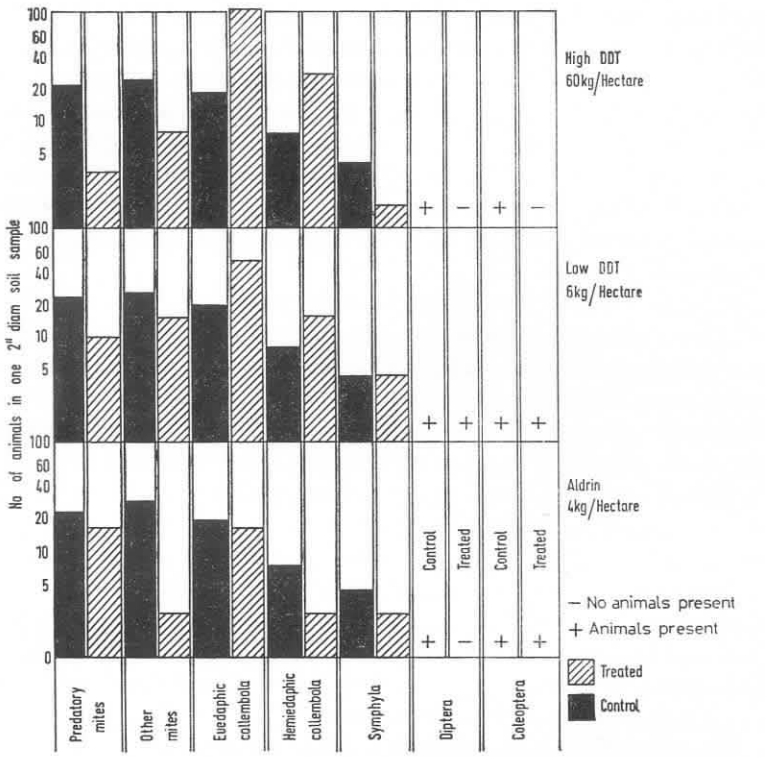

FIG. 2. Effects of DDT and Aldrin on soil animals (one year after treatment).

treated with DDT. The greatest differences in numbers are in the surface-dwelling species; populations of the more sluggish euedaphic species are less affected. There seems little doubt that the increased number of springtails directly reflects the decreased number of mites which are their principal predators; in field experiments there was usually a time lag between the fall in numbers of predatory mites and the increase in numbers of springtails (Edwards 1963).

More symphylids and root aphids are killed by DDT than by aldrin or

dieldrin, but DDT kills fewer fly and beetle larvae; numbers of nematodes, and enchytraeid worms are almost unaffected by DDT. Some workers (Fleming & Hadley 1945, Greenwood 1945, Baker 1946, Doane 1962) found that very large doses of DDT in soil killed some earthworms, but in our experiments doses, as high as 60 lb a.i./acre (68 kg/ha) had no effect at all. Thus DDT probably does not seriously change the rate at which leaves break down in soil; the smaller populations of saprophagous mites it causes are probably more than compensated for by the increased numbers of springtails. Other groups of soil invertebrates are not seriously affected, although the killing of predatory mites might accentuate some pest problems.

The effects of lindane or BHC are rather similar to those of DDT, except that BHC is less lethal to predatory mites than DDT and more lethal to springtails; hence increased numbers of springtails from predatory mite mortality is much less, and usually confined to a very few species. In some experiments, springtails did not increase at all after BHC applications. BHC is a much more efficient general soil insecticide than DDT, killing more beetle and fly larvae and root aphids. Both insecticides are however almost equally effective against lepidopterous caterpillars and symphylids. There is no apparent effect of BHC on enchytraeid worms, nematodes or earthworms.

Chlordane and heptachlor are closely related, heptachlor being a purified constituent of technical chlordane. Both chemicals kill some predatory mites and a large proportion of the saprophagous mites; they have little effect on the euedaphic springtails but almost eradicate the hemiedaphic species. They are also both very lethal to fly and beetle larvae. A different feature from those of the other chlorinated hydrocarbon insecticides is that both earthworms and enchytraeid worms are readily killed by these chemicals, especially by chlordane (Hopkins & Kirk 1957, Doane 1962); nematodes appear to be unaffected by either insecticide. Earthworms and enchytraeids are important in maintaining soil fertility so it is not very desirable to destroy them with persistent chemicals; fortunately neither of these insecticides is much used in Great Britain, so harmful residues are unlikely to occur.

The potential hazard of the chlorinated hydrocarbon insecticides has led to their use being restricted (MAFF report 1964); consequently the less persistent organo-phosphorus and carbamate insecticides are now being considered as possible substitutes, particularly for wireworm and cabbage root-fly control. The chemicals being considered for soil applications include parathion, diazinon, menazon, carbaryl, zinophos, sumithion

disulfoton, phorate and certain new, more persistent proprietary materials. As yet there is information on the effect of only the first four of these insecticides on soil animals, but investigations are under way on the others. Parathion and diazinon have very similar effects on soil animals; both kill species of most groups and are particularly lethal to symphylids. Diazinon is rather less effective against coleopterous larvae but kills root aphids very readily. Parathion can also kill earthworms, so populations are decreased in treated soil; it also kills some nematodes and enchytraeid worms, but the reductions are not usually serious.

The effects of menazon on soil animals were studied by Raw (1962), who found no effect on any animals other than the aphids against which it is normally used; it is very much more specific than any of the other insecticides that have been investigated and seems to be the sort of chemical that is most suitable for applying to soil. Of the carbamate insecticides, carbaryl has been quite extensively investigated for action against soil animals (Aspock & An der Lahn 1963). It appears to have no effect on the predatory mites or on saprophagous mites but is toxic to all kinds of Collembola and lethal to lepidopterous caterpillars. It is very toxic to earthworms, raising distinct ulcers on their bodies. Carbaryl probably only reaches the soil however, by falling from sprays used in orchards, but the results of such chemical fallout, which kills earthworms, may well resemble the effects of copper fungicides in orchard soil (see p. 252).

It should be noted that none of the pesticides yet studied except the fumigants can completely eradicate animals from soil and the effect of fumigation is transient.

IV. INDIRECT RESULTS OF PESTICIDE RESIDUES IN SOIL

Firstly, killing one kind of soil animal can indirectly influence numbers of other species; for instance killing the predatory mites in soil with DDT greatly increases numbers of Collembola. There are other comparable situations, some of which have caused increased pest attack or even created pests, as in the classical example of how fruit-tree red spider became a pest, when DDT was widely used on fruit trees and killed off the predatory mites that previously held the red spider in check.

A springtail, *Sminthurus viridis*, is an economic pest of lucerne in Australia. When Wallace (1959) tested various insecticides to control this species he found that whereas BHC treatments decreased numbers, DDT applications increased numbers many times, because it killed the principal

predator, *Biscirus australicus*, a Bdellid mite, and BHC did not. Klostermeyer & Rasmussen (1953) tested the effects of large doses of DDT (10, 24, 119 lb a.i./acre *i.e.* 11·5, 27, 130 kg/ha respectively), BHC (3, 15 lb a.i./acre *i.e.* 3·5, 17 kg/ha respectively), chlordane (8, 15, 75 lb a.i./acre *i.e.* 9, 17, 85 kg/ha respectively) and aldrin (3, 60 lb a.i./acre *i.e.* 3·5, 68 kg/ha respectively) on the growth and yield of potatoes and Black Valentine beans. In the first year of cropping, the insecticide did not affect growth, even though some plots were treated with such large doses. In the second season, the potato and bean plants on the plots treated with large doses of DDT were almost killed from attacks by two-spotted mites, *Tetranychus bimaculatus* Harvey. Many of the plants on plots receiving smaller doses of DDT were also killed and a similar effect was noticed on plots treated with the largest dose of chlordane. There was evidence that the larger the dose of insecticide, the larger the number of mites attacking the plants and the greater the damage to the crop. The authors of the paper interpreted their results as evidence that the insecticides adversely affected the growth of the crops, but in the light of our newer findings of the effects of DDT, BHC and chlordane on predatory mites, there seems little doubt that these attacks by the two-spotted mites occurred because the insecticides decreased numbers of the larger predatory mites. The two-spotted mite spends part of its life cycle hiding in soil, where it is often attacked by predatory mites; during the first season in this experiment there had been no insecticides to kill any predatory mites in the previous winter, so there was no difference in attack by the two-spotted mites in the different treatments. In the second season there were few predatory mites in some plots with large doses of insecticides hence, numbers of two-spotted mites increased during the winter in these. Thus the application of large quantities of insecticides ultimately caused heavy pest attacks and almost complete loss of some crops.

Stone (1953) recorded another instance of the use of insecticides increasing pest attack. With the increasing use of soil insecticides for control of the sugar-beet wireworm *Limonius californicus* Mann. in lima bean fields in southern California, seed-corn maggot, *Hylemya cilicrura* (Rond.) attacks had noticeably increased. Stone noticed a very heavy attack by seed-corn maggot in a field that had been fumigated to control wireworms six days before planting, and in laboratory experiments he found that the sugar-beet wireworm is not only phytophagous, but also preys on the seed-corn maggot. As dipterous larvae are fairly resistant to the insecticides the increased attacks by seed-corn maggot probably resulted from the killing of their predators. A similar predator/prey relationship

was demonstrated by Lipa (1958), who found that as doses of BHC became larger so the numbers of wireworms were progressively reduced to zero, and there were correspondingly more larvae of the mangold fly, *Pegomyia hyoscyami*, and other Diptera as the wireworms disappeared.

The eggs of the cabbage root fly are eaten by some predatory carabid and staphylinid beetles, and Wright (1962) found that an aldrin and dieldrin residue of 0·65 lb a.i./acre (0·75 kg/ha) decreased the population of beetles without affecting the pest directly; this caused 15 per cent more damage to the brassica crop from cabbage root fly than in soil with no insecticide. As larger insecticide residues gradually disappear from treated soils, they must pass through a time when comparable amounts to these experimental ones remain in soil, and increased cabbage root fly damage is possible.

These examples are quoted only to show how scanty is knowledge of how soil residues can affect both the balance between soil animals, and that between soil animals and plants. They may not be typical of the effects of chemical residues in soil, but they do point to possible hazards and indicate that persistent biocidal chemicals should not be used carelessly, without consideration of their ecological effects. This is not to deny that pests can often be controlled by chemicals without such ecological upset, when the chemicals are selective and do not leave unduly persistent residues.

The role of soil animals in maintaining soil fertility is still not defined, so that any attempts to interpret the changed numbers of soil invertebrates in terms of changed fertility are largely speculative. Certainly it seems likely that earthworms play an important part in soil formation and turnover, and we have seen that copper fungicides, heptachlor, chlordane, carbaryl, parathion and simazine all kill earthworms and are more or less persistent in agricultural and orchard soils. Although Raw (1962) recorded a large effect of copper residues on numbers of earthworms and hence soil structure in orchard soil, there was no obvious influence on yield of fruit accompanying this effect.

If direct reseeding of unploughed land cleared of vegetation by weedkillers becomes general practice, earthworms will probably become much more important in maintaining a satisfactory soil structure, and killing them by chemical residues will become increasingly important and undesirable.

In an attempt to see whether insecticide residues changed the rate at which leaves break down in agricultural soils, disks of various leaf tissues were buried in soils treated with small amounts of aldrin and DDT. The

disks were in batches of fifty and each batch was enclosed in a nylon bag with one of several different meshes, usually 0·5 mm, 1·0 mm, and 7·0 mm. The largest mesh bags allowed most soil invertebrates including earthworms to feed on the disks, whereas the smaller ones excluded various sections of the soil fauna. The bags were dug up at two-monthly intervals and the disks examined either visually or photometrically to estimate how much of each disk had been eaten, the results being calculated in terms of percentage disappearance.

Fig 3 summarizes the rate at which oak leaf disks disappeared when confined in bags with a mesh of 0·5 mm, which allowed only the mites, springtails and smaller invertebrates to attack them. The disks in DDT-

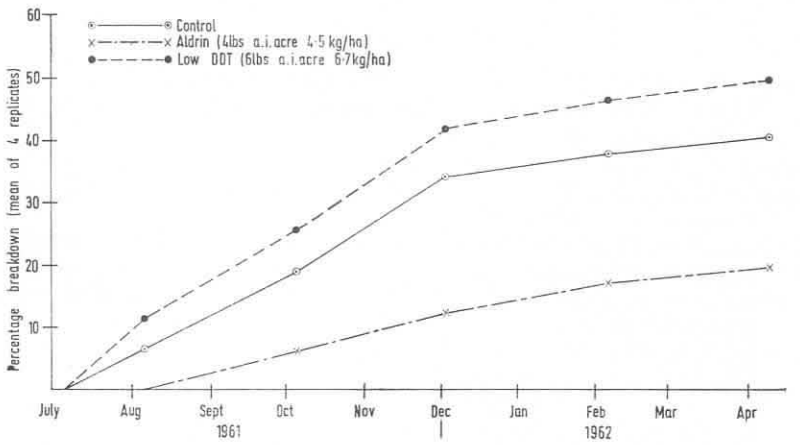

FIG. 3. Breakdown of oak leaf disks in insecticide treated soil.

treated plots disappeared faster than those in untreated soil, and those in aldrin-treated soil very much slower; this corresponded very closely with the numbers of springtails present in these soils. When the disks were examined every two months the animals most commonly found feeding on them within the bags were springtails (Edwards & Heath 1963).

Thus, in some circumstances, aldrin and DDT in soil can alter the rate of leaf breakdown, because a similar pattern occurred for other leaf tissues in this experiment. It must be noted, however, that the rate of breakdown changed only when earthworms were excluded from feeding on the disks, and earthworms are not affected by either insecticide. Mites and springtails are probably only responsible for about 20–30 per cent of the total leaf breakdown in soil, so unless earthworms were absent or few

in numbers it is unlikely that breakdown due to the reduced numbers of arthropods would be much slowed. Nevertheless, many arable soils do not have large numbers of earthworms, so it is possible that the return of plant material to the soil may be slowed down, if the chemical residues greatly affect soil animals.

Although the continued widespread and haphazard use of persistent chemicals that may reach the soil could carry dangers, there is little evidence that micro-organisms, soil animals, plants or indirectly, soil fertility, have yet been adversely affected. Nevertheless, we need very much more information on the effects of these chemicals on the biological processes in soil, and such chemicals should only be used with discrimination.

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